Reconstruction accuracy of the surface detector of the Pierre Auger Observatory

The Pierre Auger Collaboration
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Auger Surface Detector

**calibration:** VEM = Vertical Equivalent Muon
1 VEM ~ 100 pe/PMT

Arrival direction: time of flight

Energy estimator: particle density at 1000 m: $S(1000)$

3 photomultipliers detect the Cherenkov light emitted in the water
Angular Resolution

computed on an event by event basis

\( \theta, \Phi \) and \( \sigma_\theta, \sigma_\Phi \)

from fit of arrival time of the first particle in the tank.

based on:

◊ Parabolic shower front Model

◊ semi-empirical model for the uncertainty in the time measurement in each detector.

( C. Bonifazi, et al astro-ph 0705.1856 )

Angular Resolution: angular radius that would contain 68% of the showers coming from a point source.

space-angle uncertainty computed from \( \sigma_\theta \) and \( \sigma_\Phi \) as:

\[
F(\eta) = \frac{1}{2} \left[ \sigma_\theta^2 + \sin^2(\theta) \sigma_\Phi^2 \right]
\]

\[
AR = 1.5 \sqrt{F(\eta)}
\]
Angular resolution on an event by event basis

- Improves with the event multiplicity and zenith angle for events with 6 or more stations and $\theta > 20^\circ$

AR $< 0.9^\circ$
check on Angular resolution (I): “twin” tanks

We reconstructed the same showers twice, each time using one of the pairs of stations located 11 m apart.

The angular resolution obtained is in agreement with the event by event estimation:

\[
d p = e^{-\frac{\eta^2}{2\sigma^2}} d\left(\cos(\eta)\right)
\]

The space angle difference between the two reconstructions is distributed as:

<table>
<thead>
<tr>
<th>#</th>
<th>AR doublets [°]</th>
<th>AR SD-only [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.14 ± 0.02</td>
<td>1.52 ± 0.02</td>
</tr>
<tr>
<td>4</td>
<td>0.87 ± 0.05</td>
<td>0.92 ± 0.03</td>
</tr>
<tr>
<td>5</td>
<td>0.73 ± 0.06</td>
<td>0.68 ± 0.04</td>
</tr>
</tbody>
</table>

The angular resolution obtained is in agreement with the event by event estimation.
check on Angular resolution (II): Hybrid data

comparison between hybrid and SD only reconstruction

(Hybrid resolution \(\sim 0.9^\circ\) \(\sigma \sim 0.6^\circ\) subtracted in quadrature).

\[
AR = 1.5 \sqrt{\sigma^2 - 0.6^2}
\]

Provides an absolute check on the reference system.

FD mirrors pointing checked with stars and reconstructed laser shots \(\langle 0.3^\circ \rangle\)

<table>
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<th>(AR_{hybr}) [(^\circ)]</th>
<th>(AR_{SD-only}) [(^\circ)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.71 ± 0.05</td>
<td>1.54 ± 0.01</td>
</tr>
<tr>
<td>4</td>
<td>1.49 ± 0.07</td>
<td>1.03 ± 0.01</td>
</tr>
<tr>
<td>5</td>
<td>1.3 ± 0.1</td>
<td>0.92 ± 0.02</td>
</tr>
<tr>
<td>6</td>
<td>1.0 ± 0.1</td>
<td>0.62 ± 0.01</td>
</tr>
</tbody>
</table>
S(1000) as energy estimator and its uncertainty
Building an energy estimator for a Ground Array

Sampled signals have to be used to estimate:
Core Position and $S(R_{\text{ref}})$ with $R_{\text{ref}}$ a reference distance.

For every event there is an $R_{\text{optimum}}$ for which $S$ fluctuations (due to the unknown LDF shape) are minimized.

$< R_{\text{optimum}} > = 1000 \text{ m} \quad \text{Non Sat. Events}$

$< R_{\text{optimum}} > = 1600 \text{ m} \quad \text{Sat. Events}$


$S(1000)$ will be our energy estimator.

Reconstruction:
$S(1000)$ from fit of NKG-like LDF

$\beta$ slope of the LDF:
$\beta = \beta(\theta, S(1000))$
$\sigma_\beta = \sigma_\beta(S1000)$

Parametrized from data.
uncertainties of the energy estimator

Shower-To-Shower: fluctuations of $S(1000)$ for fixed primary energy and composition caused by shower physics

Model and energy independent shower to shower fluctuations of $S(1000)$ at the level of 10%
uncertainties of the energy estimator

reconstruction uncertainties:

Statistical:
sampling fluctuations in signal sizes (finite area of detectors)

obtained from the LDF fitting uncertainties

Systematic:
caused by the uncertainty in the shape of the LDF on an event by event basis

event reconstructed $N$ times with LDF slope ($\beta$) sampled from a Gaussian distribution centered around the predicted value and $\sigma = \sigma_\beta$
uncertainties of the energy estimator

reconstruction uncertainties:

Statistical:
- sampling fluctuations in signal sizes (finite area of detectors)
  - obtained from the LDF fitting uncertainties

Systematic:
- caused by the uncertainty in the shape of the LDF on an event by event basis
  - event reconstructed N times with LDF slope ($\beta$) sampled from a Gaussian distribution centered around the predicted value and $\sigma = \sigma_\beta$

no dependence on zenith angle
Check on the $S(1000)$ uncertainty estimation

- Full MC simulations (Corsika-Proton-QGSJetII)

- $S(1000)_{\text{True}}$ computed simulating a ring of 18 tanks at 1000 m.

- The distribution of: \( \log(S(1000)_{\text{Rec}} / S(1000)_{\text{True}}) \)
  is fitted to a log normal distribution for each $S(1000)$.

\[ \sigma_{S(1000)/S(1000)} \text{ form MC is compared with data} \]

agreement between estimation from data and MC
Checks with Hybrids

we reproduce the dispersion around the calibration curve using the S(1000) fluctuations and FD energy resolution

◊ the dispersion around the calibration curve is related to the combined uncertainties of SD and FD

◊ using S(1000) uncertainties (sh-to-sh and reconstruction) and the 14% FD energy resolution we reproduce the observed dispersion with simple simulation

Data:
Mean = -0.015
RMS = 0.21

We understand the combined uncertainties of FD-SD.
Conclusions

Angular Resolution

- The angular resolution is experimentally determined event by event
- checked using doublets and hybrid data.
- It is better than 2 deg for $E<4$ EeV,
  1.2 deg $3<E<10$ EeV and 0.9 deg for $E>10$ EeV ($\theta>20^\circ$)

S(1000) accuracy

- Uncertainties are estimated on an event by event basis

\[
\frac{\sigma_{S(1000)}}{S(1000)} \sim 4\% \ (8\%) \ \text{at the highest energies for events without (with) saturated stations.}
\]

- At the highest energy the uncertainties of the energy estimator are dominated by shower to shower fluctuations.